

TITLE: SYSTEM AND METHOD TO LIMIT MAXIMUM DUTY CYCLE
 AND/OR PROVIDE A MAXIMUM VOLT-SECOND CLAMP

TECHNICAL FIELD

5 The present invention relates to electrical circuits and, more particularly, to limiting a maximum duty cycle or volt-second clamping.

BACKGROUND OF INVENTION

10 Various circuit topologies have been developed to control the flow of power and/or achieve efficient energy utilization in associated equipment. These technologies can generally be categorized as power electronics. The importance of power electronics in electrical equipment stems from its broad range of applications, including residential, industrial, commercial and communications devices to name a few.

15 Power electronics generally utilize one or more power converters to, for example, control and shape an input electrical signal into another electrical signal having different electrical characteristics, such as magnitude, frequency and/or the number of phases. With the continued advances in fabrication technologies, an increasing number of applications are making use of power converters, including power supplies as well as other power electronic converters or conditioners.

20 In some power converter applications, it is necessary to limit the maximum duty cycle of a signal generated by an associated pulse width modulator. For example, the pulse width modulator output signal is limited to a certain maximum duty cycle to avoid damage or failure of the power converter under various conditions, including transient and steady state conditions. The duty cycle controls the "on time" of the power
25 converter. The possibility for damage of the power converter is due at least in part to the transformer's inability to demagnetize at large duty cycle ratios. That is, if the duty cycle becomes too large, the magnetic core can saturate and thereby cause permanent damage to the power converter circuitry. Similar concerns exist for other inductive applications. Accordingly, it becomes increasingly important to set a maximum duty cycle accurately.
30 Thus, it becomes significant to limit the current in the inductor to avoid saturation. The flux in the inductor windings is proportion to the applied DC voltage and time, which electrical characteristics can be limited by a corresponding volt-second clamp.

Various approaches exist to limit a maximum duty cycle, typically including circuitry operative to clamp the output signal of the pulse width modulator. Operation of clamping circuitry can vary according to several factors, including, for example, accuracy and temperature stability of the clamp circuitry and associated reference voltages. The cumulative effect of such variations can amount to a sizeable tolerance in the maximum duty cycle setting.

One conventional approach for limiting maximum duty cycle is to average and compare the output signal of a pulse width modulation to a reference value. The reference value is proportional to the peak value of the comparator's output voltage. A closed loop circuit continually adjusts the duty cycle so the difference between the reference value and the average comparator output is substantially mitigated, which provides a maximum duty cycle output. Other approaches exist, but generally are unable to achieve a desired level of accuracy for either a maximum duty cycle clamp or volt-second clamp.

SUMMARY OF INVENTION

The following presents a simplified summary of the invention in order to provide a basic understanding of some aspects of the invention. This summary is not an extensive overview of the invention. It is intended to neither identify key or critical elements of the invention nor delineate the scope of the invention. Its sole purpose is to present some concepts of the invention in a simplified form as a prelude to the more detailed description that is presented later.

The present invention relates generally to a system and method for limiting maximum duty cycle and/or providing a volt-second clamp for a pulse-width modulated (PWM) signal. The system includes circuitry that provides a clamp waveform based at least in part on a first reference signal. The clamp waveform is compared relative to a reference waveform to provide a limiting signal. The reference waveform can be generated based at least in part on a second reference signal. In this way, the limiting signal has a duty cycle functionally related to the first and second reference signals, whereby the duty cycle of a PWM signal can be limited by applying (*e.g.*, ANDing) the limiting signal to the PWM signal.

According to an aspect of the present invention, one or more reference signals can be programmed by utilizing one or more respective external components. By generating the reference waveform and the clamp waveform based on the reference signals, the maximum duty cycle can be set as a function of the external component(s). Additional accuracy can be achieved by matching components (*e.g.*, a capacitors) that are employed to generate the respective clamp and reference waveforms.

According to another aspect of the present invention, a given reference signal can be fixed or variable as a function of an input control voltage. Where the given reference signal changes, a volt-second clamp is achieved by the clamp system adjusting the duty cycle of the limiting signal by an amount functionally related (*e.g.*, inversely proportional) to the change in the reference signal.

The following description and the annexed drawings set forth certain illustrative aspects of the invention. These aspects are indicative, however, of but a few of the various ways in which the principles of the invention may be employed. Other advantages and novel features of the invention will become apparent from the following detailed description of the invention when considered in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a schematic block diagram of a clamp system in accordance with an aspect of the present invention.

FIG. 2 depicts an example of a clamp system in accordance with an aspect of the present invention.

FIG. 3 depicts an example of a waveform generator that can be utilized in conjunction with a clamp system in accordance with an aspect of the present invention.

FIG. 4 illustrates an approach that can be utilized to generate a reference current for use with a clamp system in accordance with an aspect of the present invention.

FIG. 5 illustrates an approach that can be utilized to generate another reference current for use with a clamp system in accordance with an aspect of the present invention.

FIG. 6 illustrates a graph of several signals versus time in a clamp system operating in accordance with an aspect of the present invention.

FIG. 7 illustrates another approach that can be utilized to generate a reference current for use with a clamp system in accordance with an aspect of the present invention.

FIG. 8 illustrates a graph of several signals versus time in a clamp system operating in accordance with another aspect of the present invention.

5 FIG. 9 depicts an example of another waveform generator that can be utilized in conjunction with a clamp system in accordance with an aspect of the present invention.

FIG. 10 depicts an example of another clamp system in accordance with an aspect of the present invention.

10 FIG. 11 is a flow diagram illustrating a methodology for limiting a maximum duty cycle or providing volt-second clamping in accordance with an aspect of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

15 The present invention relates to a system and method to limit a maximum duty cycle and/or provide a volt-second clamp for a pulse-width modulated (PWM) signal. Depending on the circuit topology, this approach can limit the absolute duty cycle or operate as a volt-second clamp in which the duty cycle is limited as a function of a variable input control voltage, such as a line voltage. The duty cycle can be selectively programmed by setting one or more external reference components, such as one or more
20 respective resistors. Additionally, through component matching, desired clamping can be achieved with a high level of accuracy.

25 FIG. 1 is a block diagram illustrating a system 10 that can operate as either a maximum duty cycle clamp or a volt-second clamp in accordance with an aspect of the present invention. The system 10 includes a current system 12 that generates one or more reference signals that can be mirrored throughout the system 10 as well as through associated circuitry. In this example, the current system 12 generates two reference
30 currents I_{REF1} and I_{REF2} . The reference currents I_{REF1} and I_{REF2} are generated based on one or more reference components, schematically indicated at 14, which is coupled to a control voltage $V_{CONTROL}$. The control voltage $V_{CONTROL}$ can be a fixed reference voltage (e.g., a predetermined voltage level or electrical ground) or a variable voltage that can fluctuate over time, such as an input line voltage. Thus, the current system 12 generates

the reference currents I_{REF1} and I_{REF2} as a function of the reference component(s) 14. For example the reference component(s) 14 can be implemented as one or more resistors coupled to the system 10 in order to set the reference currents I_{REF1} and I_{REF2} , which can define a desired maximum duty cycle or set a corresponding maximum volt-second clamping value.

The current system 12 provides the current I_{REF1} to a waveform generator 16 and to a clamp system 18, such as through corresponding current mirrors.

The waveform generator 16 is operative to generate a waveform, such as a ramp waveform indicated at 20, which is provided to the clamp system 18. The waveform generator 16 includes one or more circuit components generally indicated at 22. The one or more circuit components 22, for example, can be one or more capacitors that can be charged as a function of the reference current I_{REF1} for use in generating the waveform at 20. For example, I_{REF1} can be applied to the capacitor(s) to respectively charge and discharge the capacitor(s) as a function of a clock signal and generate a corresponding ramp signal. The waveform generator can include an oscillator or other circuitry that can generate the clock signal as a function of the voltage across the capacitor relative to a predetermined peak voltage. Alternatively, the waveform generator 16 could be synchronized to provide the ramp signal at a frequency provided by another synchronization signal (not shown).

The clamp system 18 is operative to provide a PWM signal at 24, which has a duty cycle not greater than a maximum value. As mentioned above, the maximum duty cycle for the signal 24 can be programmed based on the reference component 14.

By way of example, the clamp system 18 includes one or more components, generally indicated at 26, that enable the clamp system to generate the PWM signal at 24 having a maximum duty cycle as provided by the clamp system. The clamp system 18 controls the duty cycle of the PWM signal at 24 as a function of the reference signals I_{REF1} and I_{REF2} . For example, one or more components 26 generate a corresponding clamp waveform as a function of the reference signals. The clamp system 18 compares the clamp waveform relative to the reference waveform to generate a limiting signal, which can be a PWM signal. The limiting signal has a programmable characteristic (e.g., a duty cycle based on the reference component 14), such that it can be applied to limit a PWM

signal 28. For example, the limiting signal has a duty cycle that can be programmed in a range from about 30% to about 80%, although other duty cycles also could be programmed according to an aspect of the present invention. The clamp system 18 generates the PWM signal at 24 as the function of the limiting signal and the PWM signal 28, such that it has a maximum duty cycle limited according to the limiting signal. The PWM signal at 28 can be provided by an associated PWM controller or other circuitry (not shown), as is known in the art.

The one or more components 26 of the clamp system 18 can be matched to the one or more components 22 of the waveform generator 16 to improve the accuracy of the system 10 in accordance with an aspect of the present invention. For example, the components 22 and 26 can be matched capacitors, meaning the respective capacitors are proportional to each other. Those skilled in the art will understand and appreciate that by implementing the waveform generator 16 and clamp system 18 in a common integrated circuit (IC) 30, the respective capacitors in the waveform generator and clamp system can be matched to a high degree of accuracy. This enables improved accuracy in the clamping function performed by the system 10 in accordance with an aspect of the present invention.

FIG. 2 is a schematic circuit diagram for a clamp system 100 that can be implemented in accordance with an aspect of the present invention. The clamp system 100 includes a capacitor C_D that is coupled to a non-inverting input of a comparator 102 corresponding to a node 103. A current source 104 provides the current I_T to the capacitor C_D . The current I_T can be generated as a function of an external reference component, such as a resistor that is coupled to the associated IC implementing the system 100. For example, a reference current can be mirrored through a current network to provide the current I_T to the clamp system 100 based on the external reference component.

Another current source 106 is coupled to the non-inverting input of the comparator 102 through an associated switch 108. The current source 106 is operative to provide another current I_D , which can be coupled through the switch 108 to sink current I_D relative to the capacitor C_D . The current I_D can be generated as a function of another reference component, such as an externally coupled resistor. A reference current

generated based on the externally coupled resistor can be mirrored through an appropriate current network to provide the current I_D .

A waveform generator 110 provides a waveform, such as a RAMP signal, to an inverting input of the comparator 102. The RAMP signal can be generated as a function of one more components 112, including a capacitor C_T associated with the generator.
 5 The capacitors C_D and C_T can be matched capacitors (*e.g.*, having proportional capacitances) implemented in the same IC chip according to an aspect of the present invention. For example, the waveform generator 110 generates the RAMP signal by repeatedly charging and discharging the capacitor C_T with an input current I_{IN} , which can
 10 be the same or different from I_T , at a desired frequency. The current I_{IN} can be mirrored through a current network based on the same reference current used to provide the current I_T . According to one aspect of the present invention, the currents I_{IN} and I_T can be proportional (*e.g.*, equal) so that matched capacitors C_D and C_T can charge in proportionally the same amounts.

15 The capacitor C_D is charged as a function of the current I_T when the switch 108 is open and, assuming that $I_T < I_D$, C_D discharges as a function of the sum of currents $I_T - I_D$ when the switch is closed. The voltage across the capacitor C_D defines a clamp waveform at the node 103. The comparator 102 provides a limiting signal at 114 to an input of an AND gate 116. The AND gate 116 performs an AND function on the limiting
 20 signal at 114 and a PWM signal to provide a PWM output signal at 118. The PWM signal at 118 has a maximum duty cycle that is limited according to the duty cycle of the limiting signal at 114. In particular, the duty cycle of the PWM signal at 118 is limited if the limiting signal at 114 has a lower duty cycle than the signal at 118, and the PWM signal at 118 is provided the duty cycle of the input PWM signal otherwise. The PWM
 25 signal, for example, is a PWM control signal generated by an associated PWM controller, such as may control the “on-time” of a power converter or other power electronic device employing the clamp system 100.

The limited PWM signal is fed back from 118 to control the state of the switch 108, and thereby controls the charging and discharging of the capacitor C_D . For example,
 30 the switch 108 closes when the comparator output signal at 114 and the PWM signal are HIGH, and the switch 108 opens when either of the inputs to the AND gate 116 are

LOW. When the switch 108 closes, the capacitor C_D discharges according to the difference in the currents I_T and I_D . For example, when the switch 108 is closed, the current $I_T - I_D$ is pulled out of the capacitor C_D to cause the voltage across the capacitor C_D to decrease accordingly. During this same interval, the RAMP signal provided by the waveform generator 110 increases proportional to the current I_{IN} applied to the capacitor C_T . Once the RAMP signal (*e.g.*, voltage across C_T) and the voltage across C_D are equal, the limited PWM signal at 114 goes LOW, which causes the AND gate 116 to provide a low output at 118. This causes the switch 108 to open, such that the capacitor C_D charges as a function of the reference current I_T . Where C_T and C_D are matched capacitors (*e.g.*, proportional), they charge proportionally until the RAMP signal is reset based on the CLOCK pulse. That is, improved accuracy in operation can be achieved by matching the internal capacitors and current mirrors, which matching can employ substantially any ratio between components. A special case exists where $I_T = I_{IN}$ and $C_T = C_D$, as the capacitors will charge at the same rate while the switch 108 is open. Thus, the component matching between the waveform generator 110 and the clamp system 100 enables a desired high level of accuracy to be achieved for the duty cycle clamping function.

The system 100 also includes a peak voltage clamp 120 coupled to the non-inverting input of the comparator 102 through a diode 122. The clamp 120 is programmed and/or configured to prevent overcharging of the capacitor C_D according to a predetermined peak voltage of the RAMP signal. For example, if the voltage across C_D exceeds a peak voltage by a threshold level, indicated at epsilon (ϵ), the diode 122 is forward biased to shunt the voltage away from the capacitor C_D . The value of epsilon can be fixed or programmable. Typically, the clamp 120 clamps the voltage across the capacitor C_D to a value that is greater than the peak of the ramp waveform provided by the waveform generator 110. Those skilled in the art will understand and appreciate that various other approaches can be utilized to implement a suitable peak voltage clamp for the voltage across C_D .

[0] With respect to the example of FIG. 2, the AND-gate 116, the switch 108 and the comparator 102 define a loop, which is closed (*e.g.*, to enable duty cycle regulation) based on the comparator output 114 relative to the PWM duration. For example, the loop

is not closed (or regulating) unless the PWM duration is greater than a maximum duty cycle (D_{max}). So, if the switch 108 is opened by a valid short duration PWM signal, then the node 103 will cease discharging and charge C_D for the remainder of the period.

For purposes of simplification and understanding in this example, assume $C_D = C_T$ and $I_T = I_N$, although these relationships are not necessary. When the next period begins, C_D would be charged to a higher voltage than C_T . For very short PWM widths, its value will be clamped by the clamp 120 and diode 122. In a situation where the PWM width is greater than the D_{max} width and where this relationship has been existed for several previous cycles, C_D will discharge based on I_D through the closed switch 108. When C_D reaches the C_T voltage, C_D resumes charging, such that both capacitors would charge to the substantially the same voltage at the end of the period. Thus, those skilled in the art will appreciate that the know relationship between C_D and C_T and their respective starting voltages enables D_{max} to be calculated.

By way of further example, the dv/dt characteristics for both capacitors C_D and C_T are known. Additionally, C_D and C_T will start the cycle with known relative voltages since C_T is discharged abruptly by the clock signal associated with the waveform generator 110.

If the PWM width has been less than D_{max} for a sufficient number of cycles, it is likely that C_D may not start the next cycle with the substantially the same voltage as C_T (e.g., at the top of the C_T ramp voltage), but rather by an incremental voltage (ϵ) above the peak of the C_T ramp voltage. Consequently, in this situation, the first cycle in which the PWM width changes from a width that is less than D_{max} to a width greater than D_{max} , the effective clamped duty cycle (D_{clamp}) for that cycle will be incrementally greater than the steady state clamp value, which can be expressed as follows:

$$D_{clamp} = D_{max} * (1 + \frac{\epsilon}{V_{pp}}), \quad \text{Eq. 1}$$

where V_{pp} represents the peak to valley difference of the ramp voltage and D_{max} is the desired steady state clamped duty cycle. That is, the peak voltage clamp 120 and diode 122 operate to modify the clamp waveform at 114 by a predetermined amount, such that the comparator 102 provides the limiting waveform having a transient duty cycle D_{clamp} to limit the PWM signal accordingly. D_{clamp} is incrementally greater than the maximum

duty cycle (*e.g.*, as provided in Eq. 1) which facilitates a rapid duty cycle limit convergence time. For example, the condition where the duty ratio is limited as in Eq. 1 will exist for only a first limited cycle. In the first limited cycle, when the decreasing voltage of C_D intersects the increasing voltage of C_T , the voltage of C_D will track the rising voltage of C_T from then on, and the limit of the duty ratio is given by Eq. 1. If the clamped condition remains, the limit of the duty ratio is D_{\max} .

For power converter applications, the slightly lengthened duration during the first cycle should not result in core saturation because the transformer is designed to not saturate with the temporarily extended duty ratio limit. In fact, most transformer designs will encounter a hysteresis loss limit before they encounter a core saturation limit. Thus, the approach just described permits a brief (*e.g.*, single cycle) excursion to allow an increased duty ratio in a transient event, but maintain a smaller steady state limit if the operating point is sustained for a longer duration (*e.g.*, more than one cycle). An alternative approach might be to control the switch 108 as a function of the voltage at 103 instead of based on the signal at 118.

FIG. 3 is an example of a waveform generator 150 that can be implemented in accordance with an aspect of the present invention. The waveform generator 150 includes a capacitor C_T that is coupled to an input of an oscillator 152. A current source 154 provides a reference current I_T to the capacitor C_T . The reference current I_T can be generated as a function of an external component, such as a resistor.

For example, as shown in FIG. 4, a reference current I_T can be derived by coupling a resistor R_T to a programming pin 156 having a corresponding reference voltage. The programming pin 156 for example provides a reference voltage for an associated integrated circuit in which the waveform generator 150 is implemented. Those skilled in the art will understand and appreciate that the reference voltage can be a reference voltage that is proportional to any known fixed reference voltage in the IC (*e.g.*, $V_{REF}/2$).

Referring back to FIG. 3, the current I_T is operative to charge the capacitor C_T to generate a ramp waveform indicated at 158. A switch, such as a transistor 160, also is coupled to the input of the oscillator in parallel with the capacitor C_T . The transistor 160 is controlled as a function of a CLOCK signal that the oscillator 152 provides to a control

input of the transistor 160. The oscillator 152 provides a CLOCK signal, such as based on the RAMP signal reaching a desired peak voltage magnitude. As a result, the RAMP output signal can be provided at 158 having a desired frequency and peak amplitude level. Those skilled in the art will understand and appreciate other oscillator topologies that can be utilized to generate a desired reference waveform in accordance with an aspect of the present invention.

FIG. 5 illustrates an approach that can be utilized to provide the reference current I_D for the clamp system of FIG. 2 can be generated in accordance with an aspect of the present invention. In this example, a resistor R_D is coupled to a programming pin 170 of an associated IC. For example, the IC includes the waveform generator and the clamp system in accordance with an aspect of the present invention. The resistor R_D is coupled between a reference voltage V_{REF} (or a voltage proportional to the reference voltage) and a programming pin, which provides a predetermined voltage, so as to generate the reference current I_D . For example, the programming pin 170 corresponds to a fixed reference voltage (e.g., $V_{REF}/2$) that is less than the voltage V_{REF} to which the resistor R_D is coupled. Associated circuitry, schematically indicated at supply 172 provides the fixed reference voltage $V_{REF}/2$.

Referring back to FIG. 2, those skilled in the art will be appreciate that the system 100 seeks to maintain a zero charge change on a cycle-by-cycle basis for the capacitor C_D . Consequently, the duty cycle D can be expressed as:

$$D = \frac{I_D}{I_T} = \frac{R_D}{R_T}. \quad \text{Eq. 2}$$

That is, the duty cycle can be programmed based on the ratio of the two external resistors R_T and R_D in accordance with an aspect of the present invention.

FIG. 6 is a graph of various signals in a clamp system implemented according to an aspect of the present invention. For example, with reference to the clamp system of FIG. 2, the graph depicts the relationship between the voltages across the capacitors C_D and C_T , indicated respectively at 200 and 202, and a resulting comparator output signal (e.g., limiting signal), indicated at 204. Thus, for purposes of context, FIG. 6 will be described in connection with the operation of the clamp system 100 shown and described

in FIG. 2. FIG. 6 also depicts the duration of a period, indicated at 206, for the PWM signal 204, and the corresponding duty cycle (or “on time”) at 208.

Referring between FIGS. 2 and 6, the voltage 200 across C_D initially decreases as a function of the current source 106 being coupled to the capacitor C_D through the switch 108, thereby drawing the current I_D from C_D . That is, the voltage 200 (V_{C_D}) across C_D changes according to:

$$\frac{dV_{C_D}}{dt} = \frac{I_T - I_D}{C_D}, \text{ where } I_D > I_T. \quad \text{Eq. 3}$$

Contemporaneously, during the duty cycle 208, the clamp waveform 202 across C_T increases as a function of the reference current I_T , which can be expressed as:

$$\frac{dV_{C_T}}{dt} = \frac{I_T}{C_T}. \quad \text{Eq. 4}$$

After the voltages intersect, the comparator output signal 204 (at 114 in FIG. 2) goes LOW. Those skilled in the art will appreciate that depending on the implementation, additional circuitry can be utilized to stabilize and drive the input at 114 of the AND gate 118, as depicted in FIG. 2. For example, a latch can be inserted between the comparator 102 and the AND gate 118. In this way, the comparator 102 would set the latch (not shown), which would be reset by the clock signal at the beginning of the next period. Alternatively, a comparator 102 having desired hysteresis could be utilized to provide similar operation.

Regardless of the implementation details, when the voltages 200 and 202 intersect, the switch 108 is caused to open, such that the current source 106 is no longer activated to draw the current I_D from the capacitor C_D . Consequently, during the latter portion (*e.g.*, “off-time”) of the limiting signal during the period 206, where the output signal 204 from the comparator 102 is LOW, the capacitor C_D charges as a function of the reference current I_T . Those skilled in the art will understand and appreciate that if C_D is equal to C_T and the currents provided to the respective capacitors are the same, the voltages across C_D and C_T will have an identical slope during the portion of the period 206 when the switch 108 is opened (*e.g.*, during the “off-time”), as depicted in FIG. 6. Thus, from Eq. 4, it can be shown that:

$$\frac{dV}{dt} = \frac{I_T}{C_T} = \frac{I_T}{C_D}. \quad \text{Eq. 5}$$

Those skilled in the art will appreciate that substantially proportional (*e.g.*, equivalent) slopes for curves 200 and 202 (indicative of change in voltage for C_D and C_T) can be achieved during the “off-time” of the period 208, even in circumstances where C_D and C_T have different proportional capacitances. For example, such characteristics between voltages 200 and 202 can exist by controlling the currents through C_D and C_T . For example, if $C_D = \frac{1}{2} C_T$, the same slopes can be achieved by sourcing twice the current to C_T . Alternatively, C_D and C_T can be matched to other proportional values and proportional reference currents can be generated by appropriately configuring current mirrors in the integrated circuit. Such matching and mirroring of proportional currents is facilitated by implementation within an IC chip.

The period 206 ends in response to the waveform generator 110 resetting the waveform 202, such as based on the CLOCK signal having a predetermined frequency. The comparator 102 output signal goes HIGH, corresponding to another “on-time” for next period of the signal 204 in FIG. 6, which causes the switch 108 to close. The current source 106, in turn, draws current I_D to discharge the capacitor C_D accordingly. The periodic cycle can continue to provide the limited PWM output signal (at 118 in FIG. 2) based on the comparator output signal 204 and the PWM signal, as described above.

Thus, those skilled in the art will understand and appreciate that the system 100 provides an effective maximum duty cycle (D_{\max}) by limiting the PWM signal with a duty cycle 208 that is functionally related to the resistor components R_D and R_T (*e.g.*, D_{\max} is proportional to R_D/R_T). In this way, the comparator output signal 204 operates to limit the duty cycle of PWM signal.

By way of further example, FIG. 7 depicts an alternative arrangement for generating the current I_D , which can be variable. In this approach, a reference current is set by coupling an external resistor R_D to a control voltage, such as a power input line voltage V_{IN} , such as a line input voltage. Specifically, in FIG. 7, the external resistor R_D is coupled between the line voltage V_{IN} and a program pin 220 of an IC, which IC can include a clamp system implemented in accordance with an aspect of the present invention. The program pin 220 is coupled to circuitry, schematically indicated at 222,

which is operative to provide a substantially fixed voltage $V_{REF}/2$ that is less than V_{IN} , where V_{REF} defines a fixed reference voltage of the IC. It is to be appreciated that any reference voltage different from $V_{REF}/2$ alternatively could be utilized at 222.

The reference current I_D thus is provided as a function of the voltage $V_{REF}/2$ at the

5 pin 220, V_{IN} and R_D (e.g., $I_D = \frac{V_{IN} - \frac{V_{REF}}{2}}{R_D}$). Because V_{REF} and R_D are substantially

fixed, variations in I_D are attributable to fluctuations in V_{IN} . Where the programming pin voltage is much less than V_{IN} , then the reference current I_D approximates V_{IN}/R_D , which is a reasonable approximation for $V_{IN} \gg V_{REF}/2$. Alternatively, Page: 14

10 [0]if the assumption that $V_{IN} \gg V_{REF}/2$ is not valid, then additional resistance in series with R_D could be utilized. For example, a second resistor coupled in between the pin 220 and the circuitry 222 and having substantially the same value as R_D would make

$I_D = \frac{V_{IN}}{R_D}$, irrespective of the relative sizes of V_{IN} and V_{REF} . Thus, such additional

resistance can be utilized for small V_{IN} to enhance the accuracy of the volt-second clamp.

15 From Eq. 2 and in view of the above approximation, it follows that the duty cycle D for a clamp system can be expressed as follows:

$$D = \frac{I_T}{I_D} = \frac{I_T * R_D}{V_{IN}} \quad \text{Eq. 6}$$

OR

$$D * V_{IN} = I_T * R_D = \text{Constant}. \quad \text{Eq. 7}$$

20 Thus, Eqs. 6 and 7 demonstrate that the clamp system also operates a volt-second (or volt-duty) clamp in accordance with an aspect of the present invention. Those skilled in the art will understand and appreciate that the clamp system provides an accurate clamping function in response to perturbations of the circuit, such as a change in V_{IN} or a forced synchronization of RAMP signal. Advantageously, such clamping can occur

25 rapidly, such as within about one PWM period (or clock cycle) from such a perturbation. In response to a change in V_{IN} , for example, such clamping is achieved by modifying the duty cycle D to maintain the constant relationship as indicated in Eq. 7.

By way of example, FIG. 8 is a graph (similar to FIG. 6) illustrating operation of a clamp system implemented as volt-second clamp in accordance with an aspect of the present invention. To facilitate understanding of such operation, FIG. 8 will be described with reference to FIGS. 2, 7 and 8. An input voltage 230 is employed in connection with an external resistor to generate a reference current (*e.g.*, I_D in FIG. 7) for the clamp system. The graph of FIG. 8 also depicts a reference waveform voltage 232 (*e.g.*, across the capacitor C_T in FIG. 2) that is provided as an input to the comparator 102 as function of another reference current I_T . The clamp system also generates a clamp waveform 234, which is compared relative to the reference waveform 232 for providing a limiting signal 236 that can be applied to limit a PWM signal in accordance with an aspect of the present invention. The limiting PWM signal 236 (*e.g.*, provided by the comparator 102 in FIG. 2) has a period 238 (*e.g.*, based on a clock cycle or other synchronization) and a duty cycle 248, which is functionally related to the voltage of signal 230 and the relationship between the waveforms 232 and 234. As mentioned herein, the voltage waveforms 232 and 234 across the respective capacitors are functionally related to reference currents that vary according to one or more external resistors. The resistors thus can be set by the user to provide a desired maximum duty cycle.

In the example of FIG. 8, the duty cycle remains substantially constant until the signal 230 changes, namely, by increasing from a first voltage V_1 to a second different voltage V_2 . While for purposes of brevity, in the example of FIG. 8, $V_1 < V_2$, those skilled in the art will understand and appreciate that other relationships could exist between V_1 and V_2 (*e.g.*, V_2 could be less than V_1). In response to the signal 230 changing from V_1 to V_2 , the signal 234 decreases more quickly (*e.g.*, an increased negative slope). This is due to a corresponding increase in the reference current I_D , which can be proportional to the change in the input voltage 230. As mentioned above, the reference current I_D operates to discharge the capacitor C_D during the duty cycle (or “on-time”) 248 of the clamp system 100. The PWM limiting signal 236 (at 114 in FIG. 2) goes LOW after the decreasing voltage 234 across C_D reaches the increasing voltage 232 across C_T . The signal 236 thus remains LOW until the RAMP signal 232 is reset for the next period.

During the next period, the duty cycle 242 has decreased from the duty cycle 248 associated with the lower input voltage 230. In particular, the duty cycle 242 has decreased an amount that is inversely proportional to the increase in the input voltage 230, which is employed to generate the reference current I_D . Those skilled in the art will appreciate that the clamp system thus provides an accurate volt-duty clamp, which actually is a volt-second clamp, in which the input voltage V_{IN} times the duty cycle D remains substantially constant (see, *e.g.*, Eq. 7) in accordance with an aspect of the present invention. For example, as shown in FIG. 8, the clamp system operates as an accurate volt-second clamp operative to clamp the PWM signal within the next clock cycle from the perturbation of V_{IN} .

FIG. 9 depicts another example of a waveform generator 300 that can be employed to provide a RAMP signal to a clamp system in accordance with an aspect of the present invention. The waveform generator 300 is substantially similar to the waveform generator of FIG. 3, but also includes a synchronization input for receiving a SYNCH signal. Briefly stated, the waveform generator 300 includes an oscillator 304 coupled to a capacitor C_T that is coupled to receive a current I_T from a current source 306. The current source 306, for examples, generates the current I_T by mirroring a desired reference current functionally related to an external component, such as a resistor. A switching device 308 is coupled to shunt the capacitor C_T based on a CLOCK signal generated by the oscillator 304 as a function of the RAMP signal. The oscillator 304, in turn, can provide the CLOCK signal at the rate defined by the SYNCH signal or directly pass the SYNCH signal as the CLOCK signal to associated circuitry.

The SYNCH input signal can be provided by synchronization circuitry, which can be generated internally or externally relative to the IC containing the clamp system. The SYNCH signal enables a user to define a frequency of the RAMP signal that may be different from that generated by the oscillator 304 as a function of the RAMP signal relative to a predetermined peak voltage. For example, the SYNCH signal can be employed to provide a faster RAMP signal by causing the oscillator to terminate the RAMP waveform prematurely according to the faster clock signal provided as the SYNCH signal. A faster clock typically will result in a lower peak voltage of the RAMP signal since C_T will discharge more frequently.

Those skilled in the art will understand and appreciate that a clamp system implemented according to an aspect of the present invention will automatically adjust to a faster clock frequency and maintain a correct clamp value, such as programmed by one or more external resistors (*e.g.*, R_D and/or R_T). It further will be appreciated that additional
5 accuracies beyond conventional systems can be achieved by having CT be external to the oscillator circuit and matched with the capacitor of the clamp system according to an aspect of the present invention.

FIG. 10 depicts another example of a clamp system 350 that can be implemented in accordance with an aspect of the present invention. The system 350 is similar to that
10 shown and described with respect to FIG. 2. Briefly stated, the clamp system 350 includes a capacitor C_D that is coupled to a non-inverting input of a comparator 352. A current source 354 is coupled to provide a reference current I_T to the C_D through a switch device 356. Another current source 358 is coupled to sink current I_D relative to the non-inverting input of the comparator 352 through an associated switch 360. In the example
15 of FIG. 10, the switches 356 and 360 operate out of phase with each other to source and sink respective currents I_T and I_D relative to C_D according to their switch states. The currents I_D and I_T are provided as a function of reference currents defined by user-programmable external reference components, such as resistors. A waveform generator 362 provides a RAMP signal to an inverting input of the comparator 352. The RAMP
20 signal can be generated as a function of one more components, including a capacitor C_T . Matching of the capacitors C_T and C_D can be facilitated by implementing the clamp system and the waveform generator (or at least the respective capacitors thereof) in the same IC chip according to an aspect of the present invention. By matching the capacitors, an improved accuracy in the operation of the clamp system can be achieved
25 relative to many conventional systems.

The comparator 352 provides a limiting output signal at 364 as a function of the relative levels of the RAMP waveform (*e.g.*, the voltage across C_T) and clamp waveform (*e.g.*, the voltage across C_D). The limiting signal at 364 and a PWM signal are provided to inputs of an AND gate 366. It is to be appreciated that the comparator 352 could be a
30 hysteretic comparator or a latch could be employed at the comparator output to facilitate providing a stable limiting signal to the AND gate 366. The AND gate 366 generates a

limited PWM output signal at 368, which is limited according to which of the input signals has a lower duty cycle. That is, the limited PWM signal at 368 corresponds to a clamped PWM signal, which can be clamped to a maximum duty cycle or to a maximum volt-second value according to the circuit topology, as described herein. The PWM
5 signal, for example, can be generated by an associated PWM controller (not shown), such as may control the “on-time” of a power converter or other power electronic device utilizing the clamp system 350.

The limited signal at 368 also is fed back to control the state of the switches 356 and 360, and thereby control the charging and discharging of the capacitor C_D . In
10 particular, the signal at 368 is inverted, such as by an inverter 370, such that the switches 356 and 360 operate out of phase. Those skilled in the art will understand and appreciate various other approaches that can be employed to operate the switches out of phase with each other. By operating the switches 356 and 360 in this mutually exclusive manner, the clamp system 350 can more effectively operate for short duty cycles (*e.g.*, less than about
15 35%) since the C_D can discharge more quickly when the source 354 is not coupled to provide I_T to C_D .

The system 350 can also include a peak clamp 372 and diode 374 coupled in parallel with the capacitor C_D to mitigate overcharging of the capacitor C_D according to a predetermined peak voltage. For example, if the voltage across C_D exceeds a peak
20 voltage of the RAMP waveform by a predetermined threshold level, indicated at epsilon (ϵ), the diode 374 is forward biased to shunt the voltage away from the capacitor C_D . Those skilled in the art will understand and appreciate that various other approaches can be utilized to implement a suitable peak voltage clamp.

In view of the foregoing structural and functional features described above, a
25 methodology for generating a ramp (*e.g.*, up or down) signal, in accordance with an aspect of the present invention, will be better appreciated with reference to FIG. 11. While, for purposes of simplicity of explanation, the methodology of FIG. 11 is shown and described as being implemented serially, it is to be understood and appreciated that the present invention is not limited to the illustrated order, as some aspects could, in
30 accordance with the present invention, occur in different orders and/or concurrently with other aspects from that shown and described. Moreover, not all illustrated features may

be required to implement a methodology in accordance with an aspect of the present invention. It is to be further understood that the following methodologies can be implemented in hardware, such as one or more integrated circuits (*e.g.*, analog and/or digital), software, or any combination thereof.

5 Turning to FIG. 11, the methodology begins at the methodology begins at 500 in which clamping circuitry is provided. The clamping circuitry can operate as a maximum duty-cycle clamp and/or as a volt-second clamp according to an aspect of the present invention. The duty-cycle and a constant defined by the duty cycle and an input voltage are programmable electrical characteristics for implementing desired clamping in
10 accordance with an aspect of the present invention.

 At 510, one or more clamp parameters are programmed. The programming of clamped parameters, for example, is implemented by coupling external components to the clamping circuitry provided at 500 to establish reference electrical characteristics for the clamping methodology. The external components, for example, can be resistors or
15 any other components or combination of components capable of setting a desired electrical characteristic (*e.g.*, maximum duty cycle) for limiting a maximum duty cycle of a PWM signal according to an aspect of the present invention. Those skilled in the art will appreciate that various types of components or circuitry that can be utilized to program corresponding electrical characteristics. After the clamping parameters have
20 been programmed at 510, the methodology can proceed to 520, which can be considered normal operation of the methodology.

 At 520, one or more reference signals are generated according to the programmed parameters. The reference signals can be reference currents, which can be fixed or variable. For example, a first current is fixed and a second current can be either fixed or
25 variable depending on the circuit topology implemented to provide the reference currents. The reference currents can be mirrored (*e.g.*, through appropriate current mirrors) throughout the clamp system and other associated circuitry based on the reference signals provided by the programming at 510. As described herein, the reference signals define clamping characteristics, such as a maximum duty-cycle or a constant associated with a
30 volt-second clamp.

At 530, a reference waveform is generated, such as a function of a first reference signal (*e.g.*, a reference current). The reference waveform, for example, is a ramp waveform (*e.g.*, a saw waveform) that is provided as a function of a first reference current and oscillates at a predetermined frequency. The frequency can be set internally or
5 otherwise synchronized to an externally generated clock signal.

At 540, a clamp waveform is generated as a function of the first reference current and a second reference current. For example, the first reference current can be utilized to generate the waveform with slope commensurate with the slope of the reference waveform during a first part of a PWM period, and the second reference current can be
10 applied to cause the wave form to have an opposing slope relative to the reference current during the remainder of the PWM period. Consequently, application of the second reference current causes the convergence of the reference and clamp waveforms. By way of further example, the first reference current is sourced to charge a capacitor and the
15 second reference current can be applied to sink current away from the capacitor. The second reference current can be supplied alone or in combination with the sourcing of the first reference current. As used herein, commensurate slope and opposing slope are intended to identify the relative signs (positive or negative) of the respective waveforms.

The second reference current can be applied according to a PWM output signal (see, *e.g.*, 580 below) provided by the clamp system. At 540, the reference waveform is
20 compared relative to the clamp waveform, such as by a comparator. The comparison results in a limiting signal at 560, which has a duty cycle that depends on the relative levels of the waveforms generated at 530 and 540. That is, the limiting waveform generated at 560 defines a maximum duty cycle for the system based on the operating parameters programmed at 510.

At 570, the limiting signal is applied to a PWM signal, such as provided by a PWM controller or other PWM modulator. This can be implemented by ANDing the limiting signal with the PWM signal. For example, the PWM signal can be a signal intended to control a power level in an associated power converter system or other of power electronic device. Thus, the methodology provides an effective mechanism to
25 limit a maximum duty cycle of the PWM signal. At 580, a PWM output signal is provided according to the limiting signal applied at 570. In this way, the PWM output
30

signal will have a maximum duty cycle according to the duty cycle of the limiting signal. From 580, the methodology can return to 520 to continue implementing the clamping function during normal operation.

Those skilled in the art will understand and appreciate that methodology is
5 flexible and adaptable to accommodate perturbations in the associated circuitry, such as change in one of the reference signals (*e.g.*, the second reference signal) generated at 520. For example, if the second reference current were to increase or decrease, the clamp waveform generated at 540 would also change accordingly (*e.g.*, proportionally) and thereby adjust the duty-cycle of the limiting signal provided at 560. As a result, the
10 PWM output signal provided at 580 can be modified based on the duty-cycle changes in the limiting signal, such that the clamping functions as volt-second clamp according to an aspect of the present invention.

What has been described above are examples of the present invention. It is, of course, not possible to describe every conceivable combination of components or
15 methodologies for purposes of describing the present invention, but one of ordinary skill in the art will recognize that many further combinations and permutations of the present invention are possible. Accordingly, the present invention is intended to embrace all such alterations, modifications and variations that fall within the spirit and scope of the appended claims.